Measurements of Vehicle Azimuth Using Acoustic Signals

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Abstract. The location of objects based on the analysis of acoustic signals is widely used in various civil and military systems. Applications that allow the users to determine the location of the sound source are used, for example, in conference rooms for automatic speaker location, enabling unattended camera control, detecting and tracking the movement of objects in area surveillance systems, etc. The paper presents a system for determining the azimuth of a moving motor vehicle developed at the Military Institute of Engineer Technology in cooperation with the Wroclaw University of Technology. The system is designed for the detection, identification and location of armored vehicles and trucks. The use of acoustic signal analysis methods to locate objects allowed for the construction of passive systems that are difficult to detect. This property is particularly important in area surveillance systems and military equipment designs.

Introduction

Technologies based on acoustic signal processing are widely used in various civil- and military systems. The analysis of the acoustic signal parameters enables the identification and localization of their sources. Solutions of this type, those which enable determination of the location of the sound source, are used to detect and track the movement of objects in a military protected areas under surveillance, to detect, identify and locate armored fighting vehicles and trucks, e.g. in anti-tank mines or in systems that locate the shooter's position etc.

The marking of the sound source relative to the measurement system is carried out by determining the direction of the acoustic wave reaching the microphone array. The problem of estimating the direction of arrival of the wave is an issue known as DOA (Direction of Arrival) and is widely described in the literature. Determining the DOA under real conditions is not a simple task due to the influence of the natural environment on the manner the acoustic wave propagates. A pressing problem is the effect of background noise, reflections and interference. A number of algorithms have been developed to solve this issue, among which we can distinguish two basic methods: using estimators of Time Differences of Arrival (TDOA) and estimators of spatial spectrum distribution [1-3]. To a large degree, the efficiency of DOA estimation depends on the fulfilment of the conditions of linearity and isotropic character of the transmission medium and the assumption that the signal source is located at a large distance, so the wave reaching the microphone array can be treated as a plane wave [4].

DOA methods

Two methods of DOA estimation are presented below. They have been analyzed in terms of their applicability in the developed system for tracking the location of motor vehicles.

The TDOA method is based on determining the time (phase) relationships between the signals received from the individual microphones of the array (microphone antenna), the geometry of the antenna and the direction of arrival of the acoustic wave. The spatial distribution of the microphones must be precisely defined so that it is possible to unambiguously determine the appropriate relationships between the received signals. For long distances between the vehicle and the microphone antenna, the vehicle can be treated as a point sound source. In free space, a wave propagates spherically in all directions from a point source. Free space means space in which the influence of other phenomena accompanying wave motion, such as reflections, refractions or wave scattering, is limited to a minimum. In such a situation, with small antenna sizes, we can assume that the incoming wave is a plane wave [2, 5].

In order to ensure the possibility of locating the object for each direction, a study was carried out for a microphone antenna consisting of 5 microphones with the same omnidirectional characteristics, arranged in accordance with Fig.1. This solution guarantees no privileged directions, and thus the same parameters in the entire measuring range (0÷360°).

Microphones marked with indexes 1, 2, 3 and 4 were placed evenly in a circle with a radius R in one plane, while the reference microphone (with index 0) was placed at the center of the array, i.e. at the origin of the reference system.

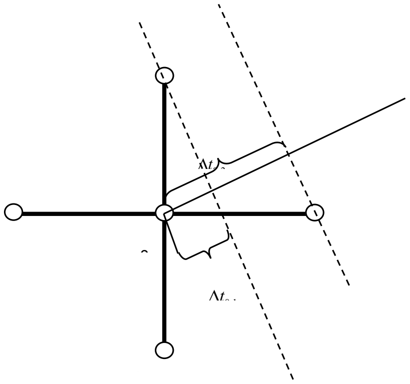

Fig.1. *Phase delay between the antenna microphones*

Determination of the direction of the arrival of the wave is conducted based on measuring the delays of signals received by individual microphones. For the three microphones (0,1,2) and (0,3,4), the following relationships result from the geometrical properties of the described system [7]:

– in the case of microphones $(0,1,2)$:

$$\sin\Phi = \frac{v\Delta t_{0,1}}{R}; \quad \cos\Phi = \frac{v\Delta t_{0,2}}{R}; \tag{1}$$

– in the case of microphones $(0,3,4)$:

$$\sin\Phi = \frac{v\Delta t_{0,3}}{R}; \quad \cos\Phi = \frac{v\Delta t_{0,4}}{R}; \tag{2}$$

where:

$\Delta t_{i,j}$ - delays between signals picked up by a pair of microphones *i, j*;
v - the speed of sound;
R - antenna radius;
ϕ - azimuth angle for the sound wave source.

The azimuth angle for the sound wave source was determined based on the knowledge of signal delay from the following dependence:

$$tg\phi = \frac{\Delta t_{0,1}}{\Delta t_{0,2}} \text{ lub } tg\phi = \frac{\Delta t_{0,3}}{\Delta t_{0,4}} \tag{3}$$

To increase the reliability of the result, all pairs of microphones should be analyzed.

There are many methods of beam formatting based on the estimation of the spatial distribution of the spectrum. Most algorithms work well with a single sound source. In a situation where there are many undesirable sound sources and a high level of noise, good results are yielded using the Capon method [2, 3]. This method is often referred to as Minimum Variance Distortionless Response (MVBR) beamforming.

As opposed to noise, the signals of the tracked signal source coming from the individual antenna microphones are correlated. Using this property, it is possible to eliminate the signal noise by estimating the cross-covariance R$_{xx}$ determined from *N* samples [8]:

$$R_{xx} = \sum_{n=1}^{N} x(t_n)x^T\,(t_n) = \frac{1}{N}X^H X \tag{4}$$

$$X = [x(t_1)\; x(t_1)\; \dots\; x(t_n)]^T \tag{5}$$

where:

t – time;
X – input signal;
H – Hermitian transpose symbol (simultaneous transposition of *T* and complex matrix conjugate).

The direction of the beam is controlled by the appropriate selection of the so-called "control vector". The output signal of the antenna can be written in the form of the relationship [8]:

$$y(t) = \boldsymbol{w}^H \boldsymbol{x}(t) \tag{6}$$

where:

t – time;
$\boldsymbol{x}$ – input signal vector;
$\boldsymbol{w}$ – weighted vector.

The total power of the antenna output signal is determined by the relationship [8]

$$P(\boldsymbol{w}) = \frac{1}{N}\sum_{n=1}^{N} |y(t_n)|^2 = \frac{1}{N}\sum_{n=1}^{N} \boldsymbol{w}^H \boldsymbol{x}(t_n)\,\boldsymbol{x}^H(t_n)\boldsymbol{w} = \boldsymbol{w}^H \boldsymbol{R}_{xx}\boldsymbol{w} \tag{7}$$

The MVDR method minimizes the power of the received signal P($\boldsymbol{w}$) outside the viewing direction θ provided that:

$$\boldsymbol{w}^H \boldsymbol{a}(\theta) = 1 \tag{8}$$

where: $\boldsymbol{a}(\theta)$ – steering vector.

The fulfilment of the above requirements is ensured by the weight vector and is determined by the relationship [8]:

$$\boldsymbol{w} = \frac{\boldsymbol{R}_{xx}^{-1} a(\theta)}{\boldsymbol{a}^H(\theta)\boldsymbol{R}_{xx}^{-1}\boldsymbol{a}(\theta)} \tag{9}$$

Substituting the above dependence into formula (7) we obtain [8]:

$$P(\theta) = \frac{1}{\boldsymbol{a}^H(\theta)\boldsymbol{R}_{xx}^{-1}\boldsymbol{a}(\theta)} \tag{10}$$

Measurement System

Having analyzed the properties of various DOA methods, expecting a large impact of noise and interference on the operation of the system, the MVDR algorithm was used, which is considered optimal due to the maximization of the signal-to-interference ratio [3].

The measurement system enabling the implementation of the above method of estimating the direction of arrival of the acoustic wave requires the use of solutions that guarantee adequate computing power. This necessity results from the adopted assumption that the system should operate in real-time, and the acceptable level of delay in the results obtained is 0.5 seconds. For this reason, a DSP processor performing all the calculations was used in the system. The process of signal sampling is particularly important for the correct operation of the system. It is necessary to ensure the synchronization of all A/D converters, which eliminates delays between signals at the stage of input signal processing. Errors resulting from the imprecise determination of the sampling moment and phase shifts in individual analogue signal processing paths are impossible to detect and remove in the subsequent stages of signal processing. Fig.2 shows a block diagram of the measuring system. The signals from the microphones are amplified and filtered. The applied low-pass filter is designed to eliminate errors resulting from the phenomenon of aliasing. Aliasing leads to irreversible distortion of the signal due to the penetration of high-frequency harmonics into the low-frequency region due to failure to meet the requirements of the Whittaker–Kotelnikov–Shannon sampling theorem. The operation of the A/C converters is controlled by the synchronization system. The DSP processor processes the received data stream from the A/D converter card and controls the amplification of the amplifiers and the operation of the synchronization system, while the results are sent via the RS485 serial link to the PC.

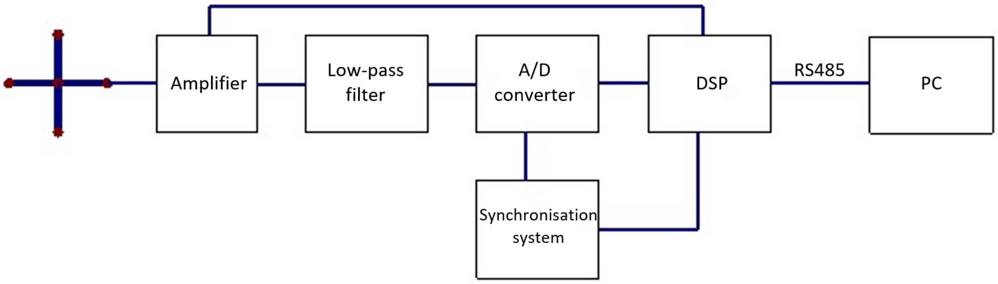

Fig. 2. Measurement system

The antenna used during the measurements is shown in Fig. 3. The distance between the microphones meets the following relationship:

$$D \leq \frac{\lambda}{2} \tag{11}$$

where: D – the distance between the microphones, λ – minimal wavelength.

***Fig. 3.** Microphone antenna*

Results

Verification of the system operation was carried out through a series of measurements of the azimuth of the vehicle moving at a constant speed in a straight line over a distance of approx. 200 m. The measurements were carried out for various distances from the antenna of the vehicle's track. Comparison of the obtained results with the theoretically calculated azimuth of the vehicle at a given point on the route made it possible to estimate the obtained measurement accuracy. Theoretical azimuth values were determined from the following relationship:

$$\varphi = arct\left(\frac{1}{\frac{vt}{d_0} + ctg\left(\frac{s_0}{d_0}\right)}\right) \tag{12}$$

where:

φ – azimuth of the vehicle
v – vehicle velocity
d_0 – distance to vehicle route (track)
s_0 – vehicle initial distance (see: Fig. 4).

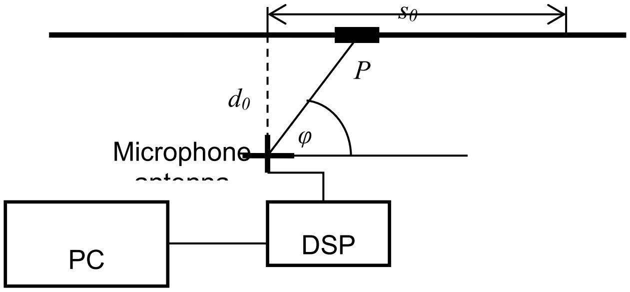

Fig.4. *Arrangement of the system components during the measurements*

Fig. 5 and 6 show: the measured azimuth values (A), the calculated values (Φ) and the measurement error determined as |A-Φ| for two directions of travel for an MTLB tracked armoured fighting vehicle with d_0 distances equal to 10 m and 80 m.

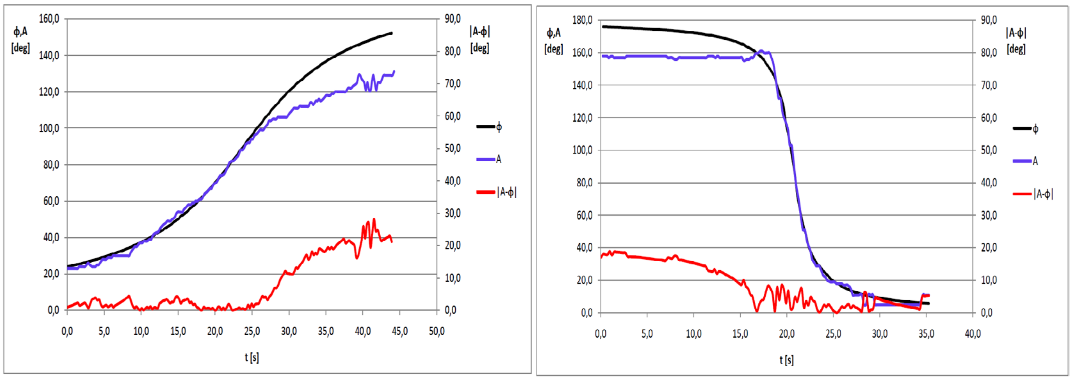

Fig.5. *MTBL vehicle traverses a distance 10 m away*

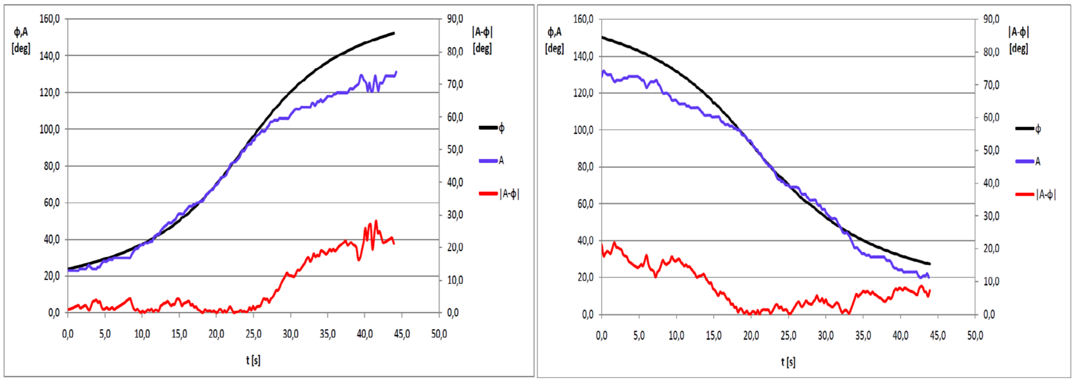

Fig.6. *MTBL vehicle traverses a distance 10 m away*

The obtained results show that the developed system enables the determination of the azimuth of the vehicle with an error under a few degrees. The errors are highly dependent on the distance of the vehicle from the microphone antenna and reach their minimum when the vehicle passes the antenna. This effect is caused by a decrease in the signal level with increasing distance, and thus a stronger influence of noise and unfavourable phenomena related to the propagation of acoustic waves. Furthermore, the observed deviations from the theoretical values for large azimuths result from the fact that in the final part, the vehicle route (track) is curved.

The estimation of the azimuth of the moving vehicle is delayed by 0.25 s. This is a satisfactory result and meets the initial guidelines.

Conclusions

The developed system allows the vehicle azimuth to be measured with satisfactory accuracy in the majority of cases. However, in unfavorable situations, the operation of the system may be strongly dependent on undesirable phenomena related to the propagation of acoustic waves. Important factors of this type include the impact of wind and terrain, with the former being capable of disturbing the direction and speed of sound wave propagation. In the case of large undulations of the terrain, the so-called dead spaces, where the sound, even at a short distance from the sound source, will be weaker or there will be no sound at all. Such a situation may make it impossible to determine the direction with the desired accuracy.

The localization of object direction based on passive acoustic signals emitted by the object is a useful method for spatial orientation, especially when visual techniques are not available. The presented approach seems to have potential applications in medical diagnostics [9] for more precise localization of musculoskeletal injuries and, on a microscopic scale, for detecting surface defects with applied special coatings [10]. Image analysis techniques, including acoustic analysis in this case, as well as statistical methods [11, 12], including non-classical approaches [13, 14], will be helpful in data analysis.

References

[1] J. Dmochowski, J.Benesty, S. Affes. Direction of Arrival Estimation Using the Parameterized Spatial Correlation Matrix, IEEE Transactions on Audio, Speech, and Language Processing 15 (2007) art. 4156192. https://doi.org/10.1109/TASL.2006.889795

[2]V. Kunin et al. Direction of Arrival Estimation and Localization Using Acoustic Sensor Arrays, J. Sensor Technol. 1 (2011) art. 7657. https://doi.org/10.4236/jst.2011.13010

[3] K. Chaudhari, M. Sutaone, P. Bartakke. Comparative Analysis of Planar Acoustic MVDR Beamformer, Int. J. Circuits, Syst. Signal Process. 13 (2019) 732-738.

[4] F. Polak, W. Sikorski, K. Siodła. Location of partial discharges sources using sensor arrays, Przeglad Elektrotechniczny 90(10) (2014) 74-77. https://doi.org/10.12915/pe.2014.10.19

[5] V. Krishnaveni, T. Kesavamurthy, B. Aparna. Beamforming for Direction-of-Arrival (DOA) Estimation-A Survey, Int. J. Comp. App. 61(11) (2013) 4-11. https://doi.org/10.5120/9970-4758

[6] S. Paulose, E. Sebastian, B. Paul. Acoustic Source Localization, Int. J. Adv. Res. Electrical, Electronics and Instr. Eng. 2 (2013) 933-939.

[7] M. Górski, G.Haza, R.Hossa, J. Zarzycki. Opracowanie układów identyfikacji i lokalizacji celu zapalnika kierowanej miny przeciwpancernej, Zakład Teorii Sygnałów Instytut Telekomunikacji, Teleinformatyki i Akustyki Politechniki Wrocławskiej, Wrocław 2010.

[8] Z. Chen, G. Gokeda, Y. Yu. Introduction to Direction-of-Arrival Estimation, Artech House, London, 2010. ISBN 978-1596930896

[9] B. Jasiewicz et al. Inter-observer and intra-observer reliability in the radiographic measurements of paediatric forefoot alignment, Foot Ankle Surg. 27 (2021) 371-376. https://doi.org/10.1016/j.fas.2020.04.015

[10] N. Radek et al. Microstructure and tribological properties of DLC coatings, Mater. Res. Proc. 17 (2020) 171-176. https://doi.org/10.21741/9781644901038-26

[11] J. Pietraszek et al. The parametric RSM model with higher order terms for the meat tumbler machine process, Solid State Phenom. 235 (2015) 37-44. https://doi.org/10.4028/www.scientific.net/SSP.235.37

[12] R. Dwornicka, J. Pietraszek. The outline of the expert system for the design of experiment, Prod. Eng. Arch. 20 (2018) 43-48. https://doi.org/10.30657/pea.2018.20.09

[13] J. Pietraszek. The modified sequential-binary approach for fuzzy operations on correlated assessments, LNAI 7894 (2013) 353-364. https://doi.org/10.1007/978-3-642-38658-9_32

[14] J. Pietraszek et al. Factorial approach to assessment of GPU computational efficiency in surrogate models, Adv. Mater. Res. 874 (2014) 157-162. https://doi.org/10.4028/www.scientific.net/AMR.874.157